3-D Finite Element Modeling of Alternating Stud Wall Construction Methods for Building Enclosures

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By

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ABSTRACT

In 2008, 99.3 Quadrillion (10^{15}) BTUs/h of energy were consumed in the United States[1]. Residential housing consumed 22% of that total, 41% of which was used for house ventilation, cooling, and heating[1]. In a house, energy is lost to the surroundings through the housing envelope. This research project analyzed a possible wall design which could reduce the loss of heat through the wall portion of the house envelope. The aim of this research was to determine if alternating studs are: a viable option for exterior walls; an efficient means of reducing heat loss from residential houses; and a cost effective method in terms of energy savings. ANSYS finite element modeling software was used to assess a total of four stud configurations– alternating studs, 2x4 studs, and two 2x6 studs models– in terms of structural deflections, structural stress and heat transfer rates. The results show larger deflections of the alternating stud configuration with respect to wind loads and point loads on the studs, though there is no concern for static failure. The alternating stud configuration model was shown to be comparable but slightly better than 2X6 models in terms of heat transfer, and is the best choice in terms of pure heat loss concerns. However, in terms of cost savings, the 2x6-24in center model was shown to be the better choice.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Every day energy becomes more and more of a concern for the global population. Whether dealing with its creation or consumption, the first law of thermodynamics cannot be ignored. The world needs to produce energy to maintain and improve the livelihood of its citizens. Yet the global population is growing at an exponential rate. To continue to power the growing world population the production of more energy will need to increase or there will need to be an increase in the efficiency of energy consumption and production. In the end it will be a combination of solutions that will make the world more sustainable. An increase in energy production will mean very little if the energy consumption is not efficient.

It is easy to grasp the notion of creating new sources, either in terms of creating new means of energy production or simple building more energy producing plants to handle the increase demand. The idea of creating more efficient means of using this energy seems simple as well, but the problem is more complex than simply creating. The refinement of older energy consumption methods can, when refined, become more efficient. In addition, old methods often come at a lower initial cost which can make it more cost efficient overall. So while new ideas and means of consumption might come into being, their cost can be so much greater than the system that they are replacing that the less efficient system will continue to be utilized.

This being said, building enclosures involve some of the oldest technology that man possesses. The idea is to build a structure to separate and protect the individual inside from the elements outside of the house. The technology has changed over time and has been greatly influenced by the availability of materials used for the construction method. In the 18th century, a new house building technology called balloon framing allowed for the cheap and efficient use of materials. The idea was to use the plentiful wood supply and make a part of the housing wall, a frame, on the ground and then put the frame up-right and attach it to other frames. This process was fallowed around the house. Then exterior sheathing layers and interior boards were attached and insulation put in-between. And since then that basic concept of house construction has stayed the same—build a frame, raise and build a wall, and then repeat until the house is finished.

There are various methods for building houses, and while there are some large contracting firms, private small house contractors build many single houses. It is in this context that this thesis addresses the issue of energy consumption. Its aim is to investigate the thermal efficiency of various wall designs that are used in construction today and assess the financial benefit of selecting one method over another. In addition to looking at heat loss, there is also need to verify that a construction method is structurally viable.

1.2 Motivation

The motivation for this investigation is energy consumption. In 2008, 95 Quadrillion BTUs/h of energy was consumed in the United States, and until 2005 energy consumption had been increasing every year. Figure 1 shows the growth in energy consumption since 1950. [1][1] It can be seen from the graph that while there are times when consumption will decrease, on the whole the energy consumption has been, for the past half century, on the rise. Figure 2 shows the distribution of energy consumption by sector: exports, residential, commercial, industrial, and transportation.[1] For there to be a significant national reduction in energy consumption, all sectors need to reduce energy consumption.

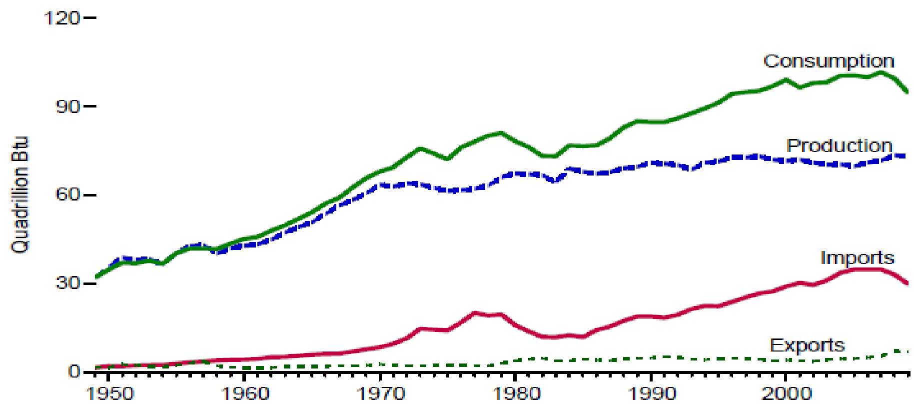

Figure 1: Growth in energy consumption and production

[1] Numbers in brackets refer to the cited source in Bibliography at the end of the thesis

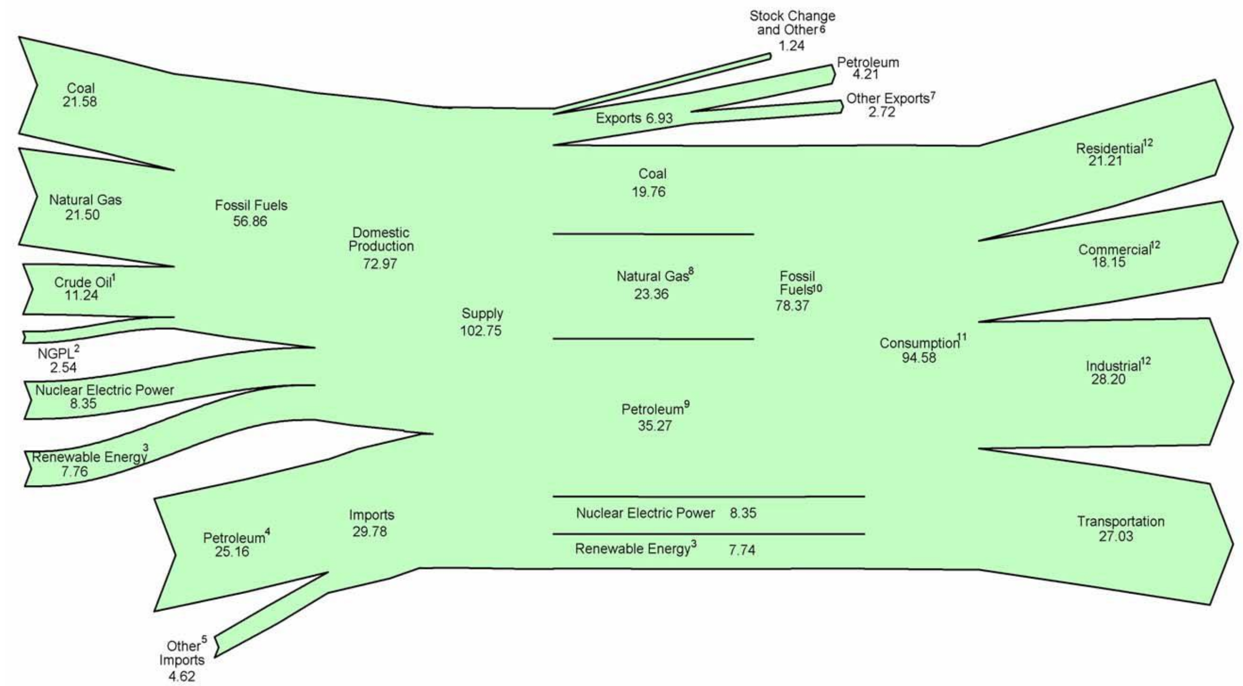

Figure 2: Flowmap of energy consumed in the United States

There are opportunities in all sectors for reduction in energy consumption. The transportation sector can incorporate of hybrid vehicles and more efficient transmissions. The industrial sector can incorporate more efficient motors and factory layouts. The commercial can utilize better materials and design energy efficient products. The residential sector can use energy efficient products and incorporate energy saving into construction and living practices. Exports are dependent on the energy policies of the energy trading partners. These are just common basic examples of possible solutions. However, some are more difficult to implement than others. While implication difficulties are beyond the scope of this thesis, there are two issues that are worth noting. One issue is the cost of implantation, energy savings cost, and the period of payback. If there is a cost benefit to implementing an energy saving method, it is more likely to be accepted. The other is public perception. While there are many ways to reduce energy consumption, the energy saving method must be adopted by the affected population. An example is if a government passed a law that people must turn off all lights after midnight, but those affected are likely not accept this law and would not be willing to obey it.

Another issue to address is the longer term effect of the energy saving method. If a product has a short lifespan, between 1-5 years, its individual impact on energy saving is small in comparison to a product that has an expected lifespan of over 25 years. Improvements in the design in terms of energy savings can be incorporated into the next iteration of the design. This is not a problem for short cycle products, which are will have only a 1-5 year lag for a more efficient product. However, the longer lifecycle products can span generations before being updated. Thus failure to incorporate a more energy efficient design will take a generation to update, if it is updated at all.

One product that has one of the longest product life spans is a house. A family can live in a house anywhere from a few months to their entire life to generation after generation. While there are opportunities for remodeling and updating, the structural framework of the house cannot be modified without essentially rebuilding the house. Thus the chosen framing method for the house is crucial. This method depends on the local climate, budget of those commissioning the house, desires of the house purchaser, and other factors. Figure 3 shows distribution of how energy is consumed in the residential sector. [1] From this graph it can be seen that, in terms of the residential sector, 49% of the energy consumed is dependent upon the design of the house itself. Space heating and air conditioning are dependent on how well the house maintains its temperature and internal air flow, which are thus a function of heat flow into and from the house.

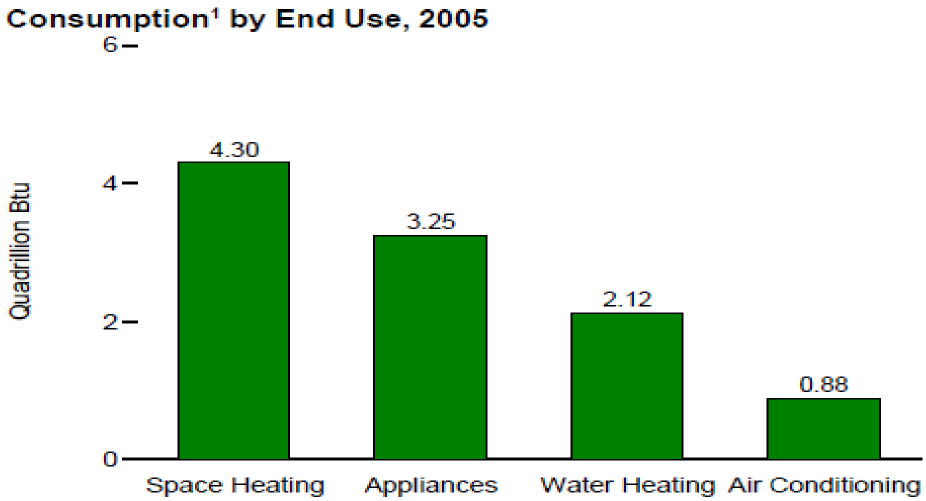

Figure 3: Energy consumption

The building envelope is the interface between the house interior and exterior, and is the barrier that insulates a house. The more thermally efficient the envelope, or barrier, the less energy is used to maintain a comfortable living environment. A threat to the efficiency of a wall is the "thermal bridge". These "thermal bridges" are the paths that are the easiest for heat energy escape from the house. Ideally a house would be a box with an insulation layer and nothing else. However, this is impractical for human living: there needs to be at least one door to enter and exit the house; there needs to be windows to let in natural light; there is a foundation upon which to build a house; there needs to be a ventilation system to let new clean air in and poorer air out; and there needs to be a framework of joints and studs to support the weight of the house roof and multiple floors. All these provide connections to the outside world and thermal bridges for energy to escape.

The largest interaction, by area, between the interior and exterior is through the exterior walls. The exterior wall is also one of the key structural components for a building and the other is the foundation. The timber studs usually provide the structural framework for the walls. Where there are no studs, the wall is ideally filled with insulation and possibly wires, pipes, and ventilation ducts, although the design should minimize how much of these are located on exterior walls. The studs provide thermal bridges for heat energy to bypass the insulation. There is thus a constant balance between the structural strength of the wall and its insulating effectiveness. However, once a design for the wall is chosen it is likely not to change until a new house is built. So while improvements in windows and doors in terms of thermal efficiency can be made, the house wall is there for the life of the house. It is for this reason that choosing the appropriate wall structure is important in terms of long term energy savings.

1.3 Literature Review

In the summer of 2009 a prospectus on a project to increase energy efficient houses built in Ohio was submitted. The focus of this purposed project was to increase not only the number of energy efficient houses, but also to increase the knowledge about energy efficient houses as a system of building components. Points that were stressed in this project proposal overlap with the aims of this thesis. One major focus is the need to quantify the effect each part of the house systems, of which the house wall is a vital component. There is a need to quantify the cost of construction and over the lifetime of the house system components. There is a desire to find the impact of each component, and this thesis aims to quantify house wall designs.[17]

In the early 1980s an energy crisis caused increased interest in energy conservation. One of the products of this shift in interest was more research into house design. Various initial concepts and research was done to quantify possible directions in house design. From windows and doors, to the ceiling and floor/basement, to the various joints and the HVAC systems, many components affect the efficiency of a house. The first key questions in building a house are the footprint and height of the building. For the same living space, one story houses have more surface area than two story houses; however it is the one story house that has lower heat losses. [10] This is because ceilings are typically better insulated than the walls. However, inclusion of windows, doors, and the insulation to the ground can change the efficiency of any idealized situation. This does give direction concerning the design of the wall, for one story houses do not need as much structural strength as would be needed for two storied houses.

First and foremost, a wall must protect those inside from the elements, rain, wind, snow, ect., outside. Thus, sheathing layers and vapor barriers must be present and attached to the exterior walls. Once a wall can adequately separate the inside from the outside, then concern for the thermal control layer can become the focus. [19] This thesis incorporated the sheathing layer in the model, which can also strength in stiffing the wall. Additional concerns are air and moisture flow through the wall; however proper installation of vapor barriers and sealing of joints can reduce these effects to insignificant amounts, if done properly. Thus, the vapor barrier was ignored and air and vapor transport through the wall will assume to be negligible in the heat transfer. Also, the vapor barrier does not provide strength to the wall.

In a wall, insulation works by creating air pockets that prevent the movement of air, because still air has a high thermal resistance. Ideally a house would be comprised of just insulation; however such advanced materials that provide structural support and insulation are expensive. Thus, a house is constructed of studs spaced evenly apart that provide the structural strength, with the insulation filled in-between. As mentioned previously, wood is a thermal bridge, or the path of least resistance to heat transfer. Fewer studs leads to fewer thermal bridges, however the strength of the house also decreases. One recommendation that is pertinent to the design of a wall is to avoid insulation voids. These voids are areas where there is no insulation in the wall and air is then able to circulate, often a product of improper installation. [10] The concern with more complex designs is that an increase in insulation gaps could be a byproduct.

In construction, the main rating for insulation is the R-value. This is the resistivity of the walls to heat transfer. The higher the R-value the greater the resistant to heat flow. Figure 4 shows the thickness for various materials to obtain an R-value of 20 (R20). The benefit of using polystyrene, batt, or sawdust insulation is evident. It also shows how much more resistive wood is to heat transfer than bricks or concrete. However, wood has more than double the R-value of common insulation materials (again the concept of thermal bridging). There has also been work done to give an R-value to various wall configurations and material selections. <u>Thermal Performance and Wall Rating</u> by Christian and Kosny of the Oak Ridge National Laboratory provides various whole wall R-Values. They also predict the impact of various conditions on the R-value for the whole wall. However, wood framing results were for only three select framing methods.

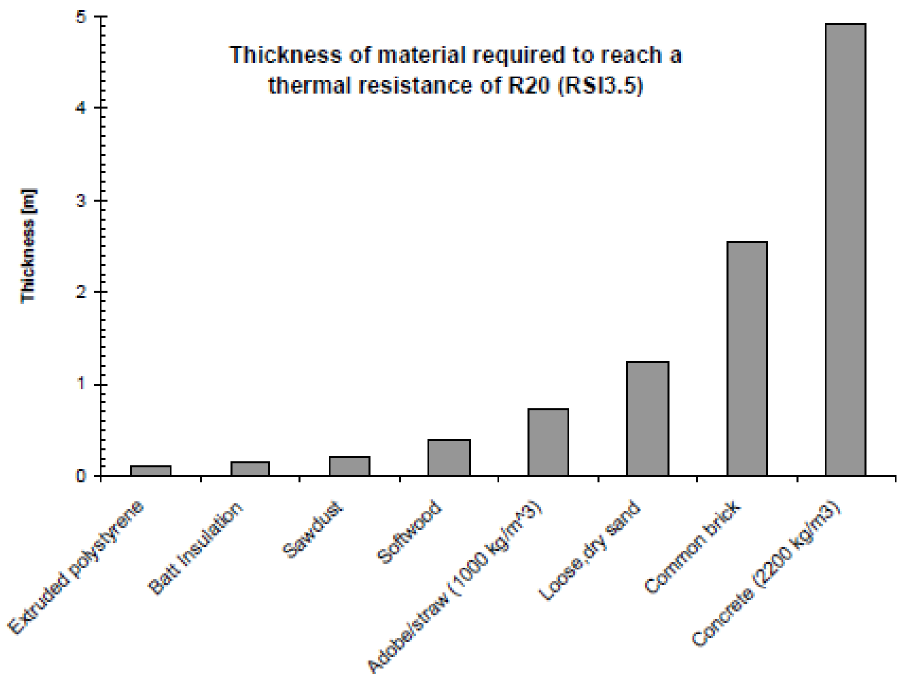

Figure 4: Comparison of the thickness of various materials required to achieve R20 [21]

Structurally there are various shapes, sizes, and configurations in house construction. The chosen method depends on the climate in terms of temperature ranges and the humidity. In the Great Lakes and Ohio Valley regions, the temperatures reach above 100F in the summer and well below freezing in the winter and shifts from dry winters to humid summers. There is also concern for strong rainstorms, with wind gusts over 60mph and heavy snowfall in excess of half a foot.[18] Any house must be able withstand these weather conditions and maintain comfortable living conditions for house owner. Current construction practice use a 2X4 and 2X6in studs and base.[3] The studs are separated either 16 in or 24 in on center. These two dimensions are chosen largely because current sheathing materials are manufactured in 8ft sections, and thus reduce waste. In some regions, mostly due to the heavy snow fall, it is required to have 2X6 studs. Most areas use the 2X4-16 in on center studs for construction.[20]

In terms of construction with a focus on energy efficiency there are two main methods: superinsulated houses, which are well insulated and airtight to minimize heat loss, and double envelope houses, which use a stud on the interior wall and stud on the exterior wall that are separated, to avoid thermal bridging. It is possible for both methods to be implemented in the same housing system. The wall improvement in this thesis fall more under the idea of the double envelope. For the double envelope, various stud configurations are possible. Figure 5 shows one staggered stud model, with a base frame width of 8 in.[10] A smaller 6 in base plate could be used, which would use less material and providing a direct comparison to standard 2X6 methods.

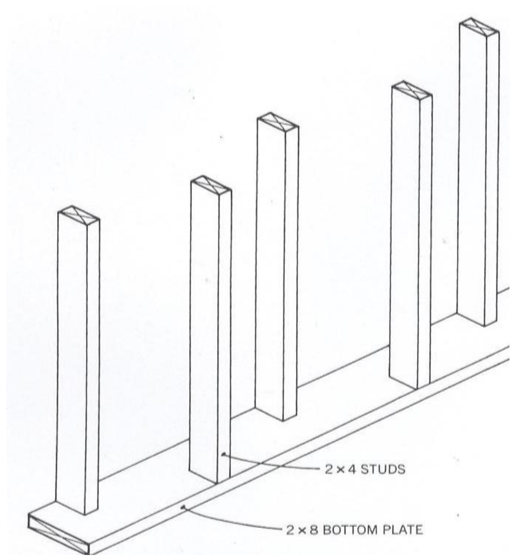

Figure 5: Double envelope stud [10]

1.4 Project Objective

The overall goal of the thesis was to investigate possible design configurations for a house wall. From the preliminary research, the most feasible alternative to current construction methods is the alternating stud configuration. The goal will be to assess the alternating stud wall configuration in comparison to the three main stud configurations that are used, namely the 2X4 and 2X6 studs at 16 in and 24 in on center apart. Figure 6 is a schematic of the three stud configurations. All walls will be designed for an 8 ft ceiling, thus the wall height will be 95.625in. The project will focus on the structural strength in terms of bending loads and heat transfer during cold months. In the end, a cost benefit analysis will be performed to compare the benefit of building a certain wall stud configuration over another.

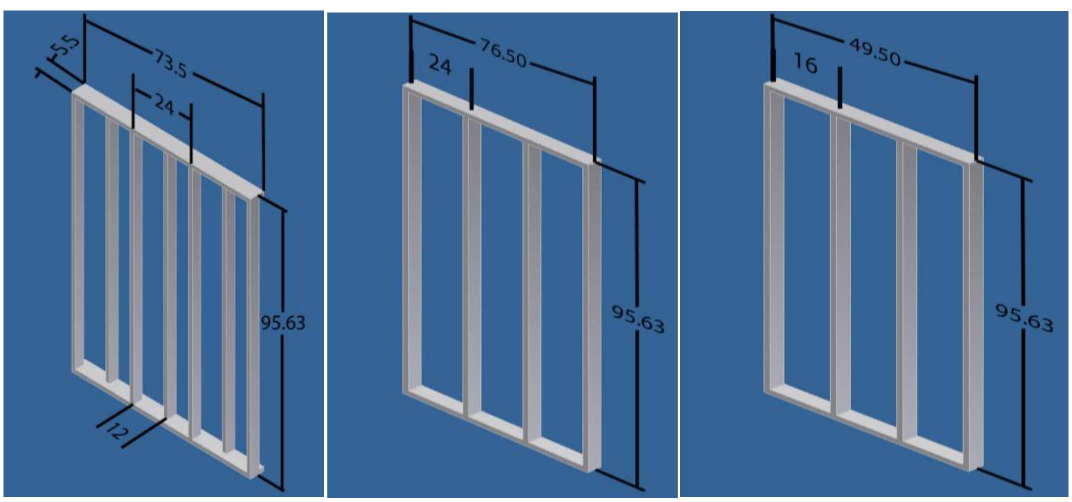

Figure 6: Computer Model of Alternating Stud

CHAPTER 2

METHOD AND MODELS

This chapter focuses on the conceptualization of the computer models. Section 2.1 covers the materials selected and provides their material properties. Section 2.2 describes the modeling methods and model configurations for the structural and heat transfer simulations. Section 2.3 describes the selection and application of loads to the models.

2.1 Materials

Various studs are used in framing, which include fir, pine, and spruce. The selection of which timber to use varies by region. White Western Pin was selected as the wood to use in this thesis, though changing the material properties of the wood is not difficult in a computer simulation. Another consideration with wood is the fact that the material is orthotropic, or the strength of the wood varies in the radial, tangential, and longitudinal directions. This is due to the grain direction in the wood, and Figure 7 shows an image of the radial, tangential, and longitudinal components in reference to the wood stud. While it would be possible to model the material as isotropic based on the tangential modulus, the inclusion of orthotropic properties is easily done in modeling the wood and provides a more accurate simulation. Thus, the orthotropic properties were included in the model. However, in terms of heat transfer there is no noticeable difference in terms of direction, and thus the stud will be treated as an isotropic material for heat transfer simulations.[11]

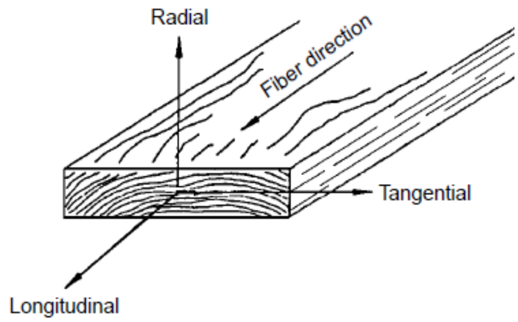

Figure 7: Orientation of wood [11]

Part of designing a wall is selecting the material to sheath it, so the effect of the selection needs to be assessed as well. There are two kinds of sheathing that are used in industry today, plywood and Oriented Strand Board (OSB). The material properties for these two vary slightly, but are made with the same dimensions. Both boards will be used in modeling to compare the selection of the sheathing layer on heat transfer and structural strength. In addition, the internal wall will use plaster board, or gypsum board. This layer seals the inside of a wall and provides a surface to paint, decorate, and hang house amenities. While used more for aesthetics and to hide wires, pipes, and gas lines, the layer could provide structural support to the wall and additional heat transfer resistance.

There are various forms of insulation used in construction. From batt insulation which is square sheets of tightly packed fibers to lose cellulous insulation which is small pieces of insulation blown into the wall.[21] The concern for both of these is insulations gaps. The batt insulation is cut to fit tightly into the wall.[19] As it is placed inside the spaces between the studs, the sides of the batt insulation can catch on the wood and leave a gap at the corner of the stud and sheathing layer. This is more likely to happen with the alternating stud, due to the more complex nature of the design. Blown insulation can also have gaps caused by not enough pressure to “fill” all the corners. However, the blown insulation would be easier to install in the weaving pattern of the alternating studs. Thus, blown insulation will be used for both the 2X4, 2X6, and alternating models.

Table 1 shows the material properties of the materials used to model the various wall formations. The cellulous insulation cannot be relied upon to provide added structural strength to the wall, and was thus not included in the structural model. The values for the Gypsum, OBS, and Plywood were obtained from Gypsum Association technical specification sheets, ILevel literature, and Encyclopedia of Materials, respectively.

Table 1: Material properties

Material	Modulus of Elasticity (E) in psi	R-Value (R) per inch[2]
White Western Pine (Stud Wood)	1,460,000	1.25
Gypsum Board (Plaster Board)	193,000	0.90
Oriented Strand Board (OSB)	1,000,000	2.64
Plywood	1,800,000	1.25
Cellulous Insulation (Blown)	----	3.70

[2] All R-values are in terms of per inch for this thesis

Table 2 shows the orthotropic modulus of elasticity and poissons's ratio for the three orientations of white western pine. Various woods can be used for studs, depending on the time of year, and supplier for the contractors. White western pine is a typical wood with average strength; other woods could be modeled in the simulations if a need was warranted.

Table 2: Orthotropic properties of white western pine

Direction	Modulus of Elasticity (psi)	Poisson's Ratio (to Tangential)
Radial	55,480	.410
Tangential	113,880	----
Longitudinal	1,460,000	.344

2.2 Computational Models

The following two sections are devoted to describing the computational methods used. Section 2.2.1 describes the finite element models and assumptions. Section 2.2.2 describes the heat transfer program and finite element models for verification.

2.2.1 Structural Models

A computer simulation model in the ANSYS finite element software package was created to simulate the affect of various structural loads to the selected stud configurations. Figure 8 shows three images of the construction of the volume meshes. The image on the left shows the mesh for the studs, in light blue, which was done first. First a volume element for each was created using keypoints at each corner of the 2X4 or 2X6stud frames, then an automated mesh was used to created 3D finite volume elements on the order of one element per quarter inch. Then the top and bottom framing were added by creating volume elements from the corner of each keypoints. It was important to select the keypoints from each stud and piece the top and bottom together, if this was not done the meshes would fail to align. This would result in a non rigid connection of the studs to the frame.

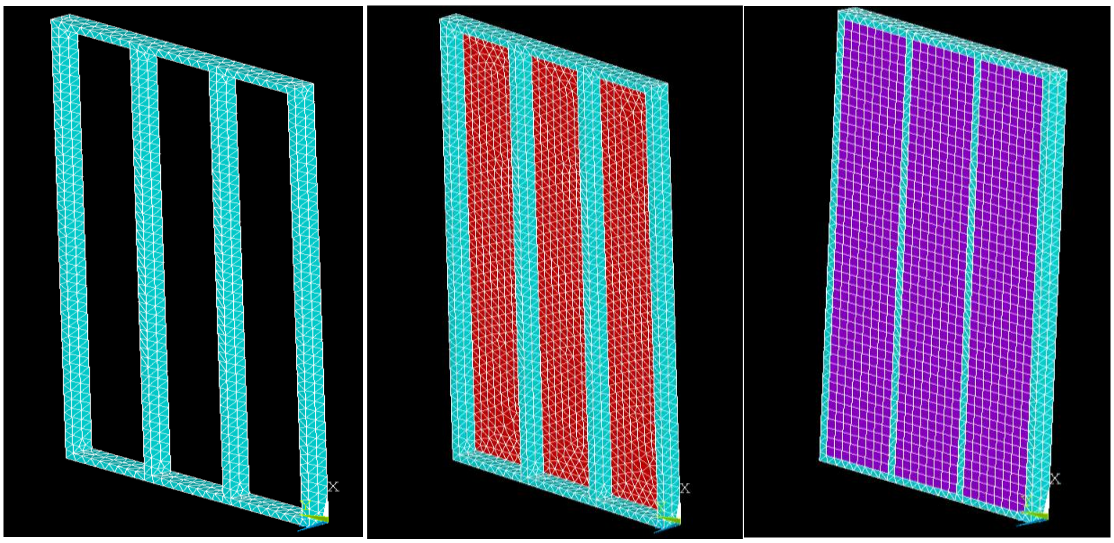

Figure 8: Elements,wood configuration, then plaster, then sheathing

The image in the middle of Figure 8 is of the gypsum board, in red, and the image on the right shows the inclusion of the sheathing layer, in purple. Using the 2D area in-between the studs coplanar to the exterior, sheathing layer, and interior, gypsum layer, surfaces a shell was created. This shell was created using the automated shell feature to create 3-D volume elements that were as thick as the desired sheathing layer and one inch square in the plane. The joining of the two layers to the stud framing was assumed to be rigid and occurred at the edge of the stud with this model.

For the alternating model, the studs volume elements were created using the same process as for the 2X4 and 2X6 model, with the exception being that the stud was split into two volume elements, one 2 in wide for the insulation and another 3.5 in wide for the 2X4 stud. This was done to account for the space where there was no stud and to ensure that the mesh aligned between the studs and the framing. The sheathing and gypsum layers were created in the same fashion. With the exception that every other stud did not have either an external or internal layer attached to it.

In total, the number of elements that were created for the four base models were on the order of 90,000. Overall, the goal in building these models was to provide a model that could have any number of loads applied to it in any direction. Also, this would allow for vertical loads to be applied to the model as well.

2.2.2 Heat Transfer Models

All the elements of the heat transfer model were simple block shapes, thus a thermal circuit was used to calculate the heat loss. The thermal circuit used is shown in Figure 9 for the alternating stud model, Table 3 provides a key for the color.

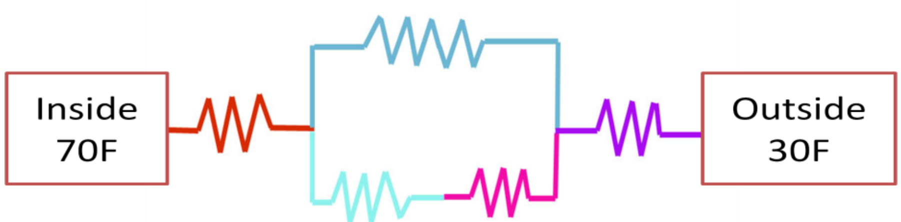

Figure 9: Thermal circuit

Table 3: Color key for thermal circuit

Color Code	
Stud	Cyan
Sheathing	Magenta
Gypsum	Red
Insulation	Blue
Insulation Gap	Pink

Using the concept that heat loss is a function of the change in temperature times the thermal resistance, Equation 1 was derived for a 2X4 alternating model.

$$q_{loss} = \frac{\Delta T}{R_{osb} + R_{gypsum} + \left(\frac{1}{\left(\frac{1}{R_{stud}} + \frac{1}{R_{gap}} \right)^{-1}} + \frac{1}{R_{insulation}} \right)^{-1}} \qquad \text{Equation 1}$$

Equation 1 was derived from the concepts of series and parallel circuits. With most materials given in the form of an R-value based on width, the conductivity needed to be derived from these R-values. In using this equation the gap was treated as a stud wall for the 2X4 and 2X6 model. The MATLAB code in Appendix A was used to calculate the heat loss for an 8 ft section of each wall, which was the lowest repeating common wall section for the various walls. In addition, various sheathing materials were used in the code. Also, to simulate a gap in the insulation caused by improper insulation the R-value was decreased for the small insulation gap in the alternating model.

2.3 Applied loads

Three applied loads were modeled, one wind load and two point loads. A wind load of 75mph was used, which equated to 0.92 psi on the whole exterior face. This was chosen because it is higher than the average high wind gusts in the Ohio region, thus providing an extreme case. This load was modeled in ANSYS as a pressure on the external surface, both on the sheathing and studs. A point load of 50lb was used to simulate a 200lb individual leaning at 20° from vertical. This provided a more extreme case of perpendicular load. This load was modeled as a point load in ANSYS at the approximate center, both vertical and horizontal, of the internal and external sheathing layers and of the stud. The top and bottom of the frame had a fixed boundary condition applied.

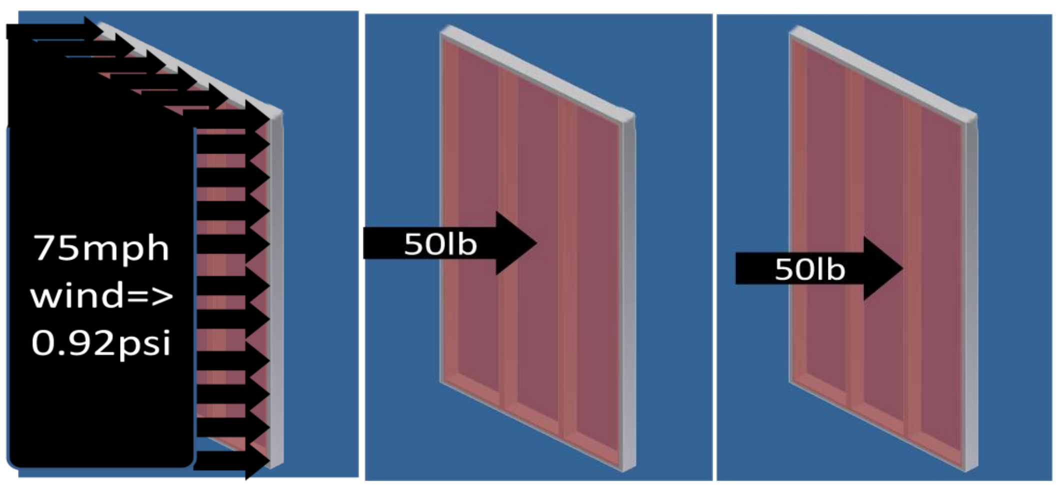

Figure 10: Application of point load

For the heat transfer analytical model, the greatest heat loss occurs during the winter months when a house owner tries to maintain a comfortable warm interior. This is the time when there is the greatest temperature difference between the exterior and interior temperatures, and thus the greatest opportunity for heat loss. An interior temperature of 70F was chosen for this thesis. The goal was to model what individuals keep as their preferred interior temperature. An exterior temperature of 30F was chosen to model a cold winter day. The average high and low temperature in Columbus during December, January, and February are 39F and 22F respectively.[6] Thus, an average temperature of 30F was used. Both temperatures are approximate boundary conditions that could change from year to year and vary from person to person and location to location.

2.4 Verifying

The computational results for the ANSYS models were compared to analytical deflection equations. The deflection of the stud was compared to a point load on a fixed beam at the midpoint beam. Equation 2 modeled this condition, assuming that the stud was isotropic.

$$deflection = \frac{Pl^3}{192EI} \qquad \text{Equation 2}$$

$$I = \frac{1}{12}bh^3$$

The deflection of the sheathing for a wind load was compared using Eq. 3 to the analytical equations for a rigid clamped plate due to point and distributed loads Equation, where the value of a, b and h are the height, width, and thickness of sheathing respectively.[4]

$$deflection = C(1-\nu^2)\frac{\rho b^4}{Eh^3} \qquad \text{Equation 3}$$

$$C = \frac{0.032}{1+\alpha^4} \qquad \alpha = \frac{b}{a}$$

The deflection of a 2X4 stud subjected to a 50 lb concentrated load was found to be on the order of 0.3391 inches. This provided the upper bound for the expected deflections. The deflection of OSB over a 30.5 in span, which occurs with alternating stud walls, with fixed edges due to a .92 psi pressure, was found to be 0.44 in. This provided an upper bound for the expected deflection due to a pressure load on the exterior house walls.

To provide a comparison for the analytical heat transfer results, an ANSYS simulation was preformed for the various wall models. Figure 11 is an image of the ANSYS model used for the alternating 2X4 model. The colors on the model follow those used in Figure 9. Symmetry was assumed in the model and applied by using a quarter of a 12in wall section. The 3D mesh was created using keypoints at each of the corners of the volume elements. In all, the model had over 97,000 elements. The eternal and internal wall thickness was included and assumed to cover the entire model. The stud and gap were cut in half along the length of the stud, this allowed for symmetry to be applied on that surface. The 70F and 30F boundary conditions were applied to the internal and external surface, respectively. No flux was assumed to be through the floor boards, which was an assumption made for the analytical model as well.

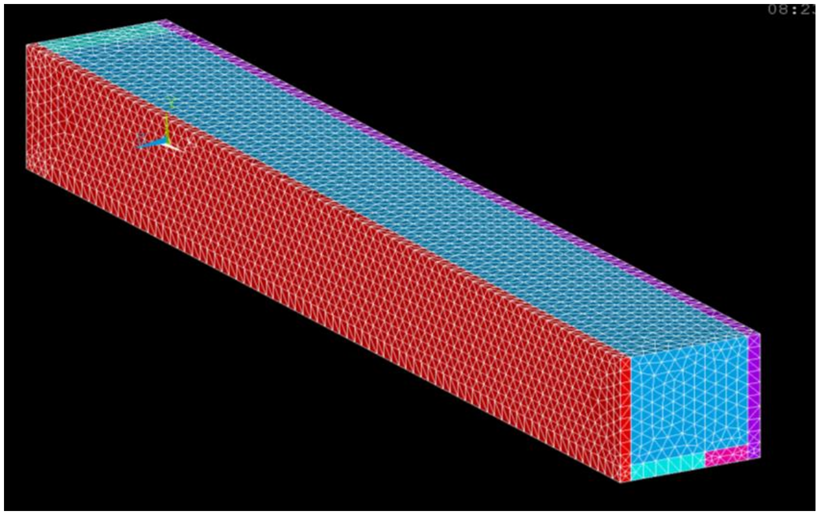

Figure 11: Thermal node model

Figure 12 shows the output from the alternating 2X4 ANSYS model using an R-value of 3 for the insulation and plywood for the sheathing layer. The plot shows the heat transfer through the wall section. From the plot, the effect of a thermal bridge is clear, with about 4.5 BTUs/h per hour per inch squared transferring through the stud and only about 2 BTUs/h per hour per inch squared transferring through the insulation. Before the stud section, the heat transfer is between 2.3 and 2.7 BTUs/h per hour per inch squared. This shows the benefit of trying to minimize the thermal bridges, or in the case of the alternating 2X4, limit the timber and increase the insulation. The final average heat transfer leaving the wall section is 2.57 BTUs/h per hour per inch squared, leading to a total heat loss of 5.12 BTUs/h per hour for the half a foot wide by 3.98ft high section. The heat transfer for the analytical models should be similar.

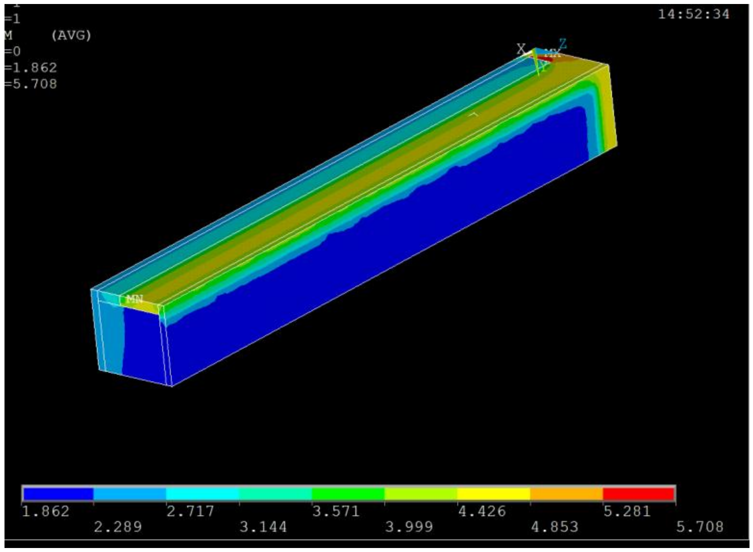

Figure 12: Output of heat transfer simulation for alternating 2X4 and 3.7 insulation (in BTUs/h per in^2)

CHAPTER 3

SIMULATION RESULTS

This chapter focuses on the results obtain from the simulations. Section 3.1 contains the results of the structural ANSYS models in term of the maximum deflections. Section 3.2 contains the results of the structural ANSYS models in terms of the maximum stresses. Section 3.3 contains the results of the heat transfer MATLAB modeling.

3.1 Structural Deflections

Figure 13 shows a sample output from the ANSYS simulations for the 2X4 model. The maximum output from these simulations was used for the maximum stress.

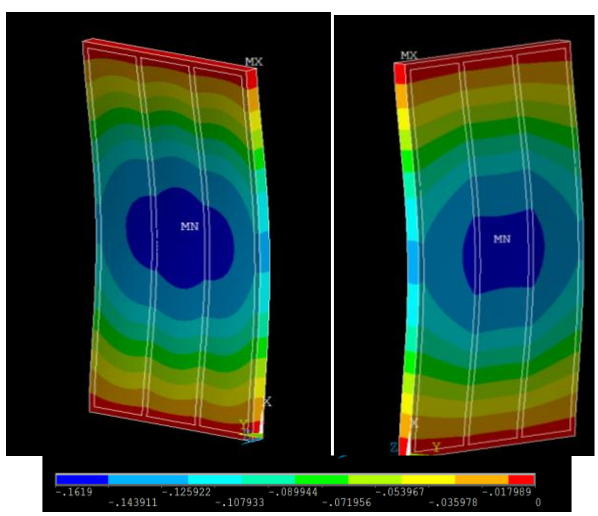

Figure 13: Deflection as a result of windload in psi (exterior left and interior right)

Figure 14 shows the maximum deflection as a result of the wind load. The 2X6-16 in center model had deflections under 0.1 in while the alternating 2X4 had deflections around 0.3 in. The 5/8 in plywood had the largest deflection for the 24in on center span. The 7/8 in plywood had the smallest deflections for each ANSYS model.

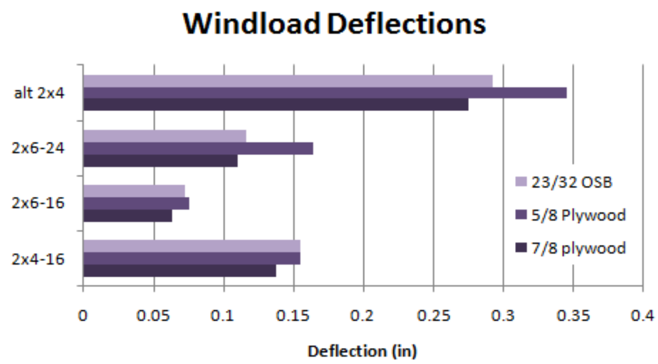

Figure 14: Wind load deflections

Figure 15 shows the maximum deflection of the studs as a result of a point load. All deflections are under .025 in, however the alternating 2X4 had deflection that was more than double the 2X4-16 in center model. Both 2X6 models had the smallest deflections, and show no significant difference between the two models. There was no significant difference in the deflection of the stud for either plywood or OSB board.

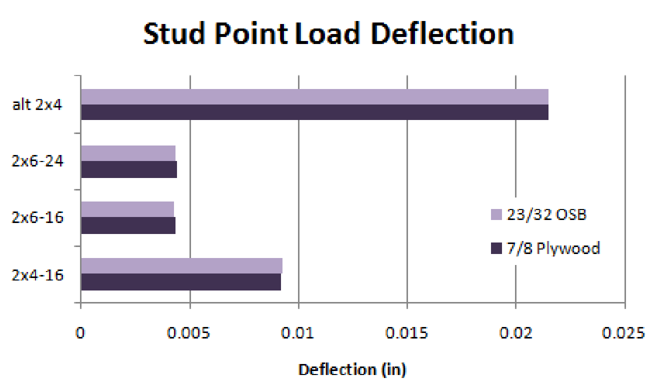

Figure 15: Stud point load deflection

Figure 16 shows the maximum deflection of the sheathing and wall board as a result of a point load. The gypsum board has the greatest deflection, an order of magnitude greater than the sheathings for the 24 in on center models. The largest deflections occurred with the alternating 2X4, whereas the smallest deflections occurred with the 2X6-16 in center model. The plywood sheathing had the smallest deflection.

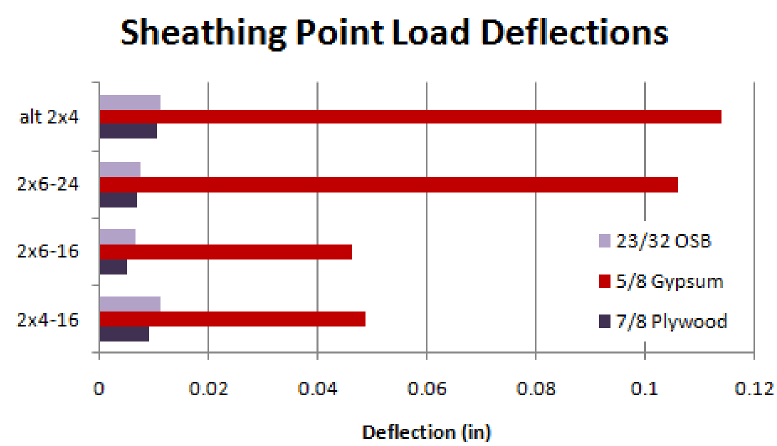

Figure 16: Sheathing point load dflection

3.2 Structural Stresses

Figure 17 shows a sample output from the ANSYS simulations for a wind load. The wind load induced the greatest stress in the wall's components. From this model it can be seen that the greatest stress occurred in the corners of the sheathing layer where the wood and the sheathing layer were attached.

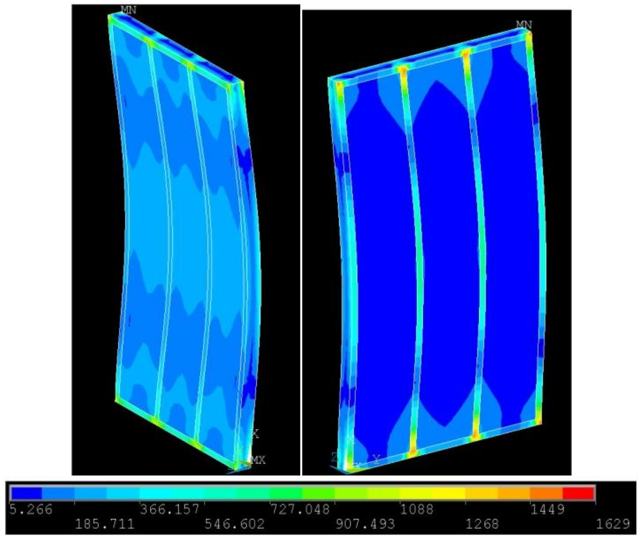

Figure 17: Stress as a result of wind load in psi (exterior left and interior right)

Figure 18 shows the maximum stress as a result of wind loads. The alternating 2X4 model had about five times greater stress than the other models. The 2X4-16 in center model had stress of about 1500 psi. The lowest stress was in the 2x6-16 in center model, of about 900 psi. There was no significant difference in stress based on the sheathings used.

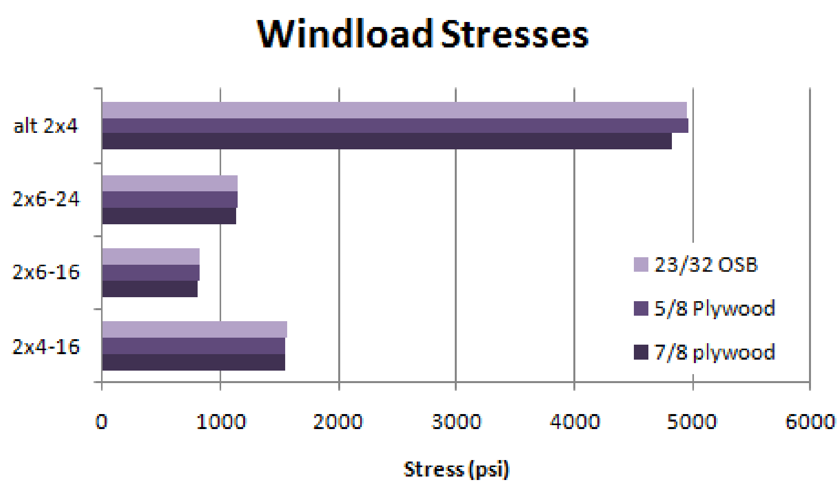

Figure 18: Wind load stress

Figure 19 shows the maximum stress as a result of a point load on a stud. The stress for all materials is under 240 psi, with the largest being the alternating 2X4 with 225 psi. The smallest stress occurs with both 2X6 models. There is no noteworthy difference in maximum stress based on the sheathing.

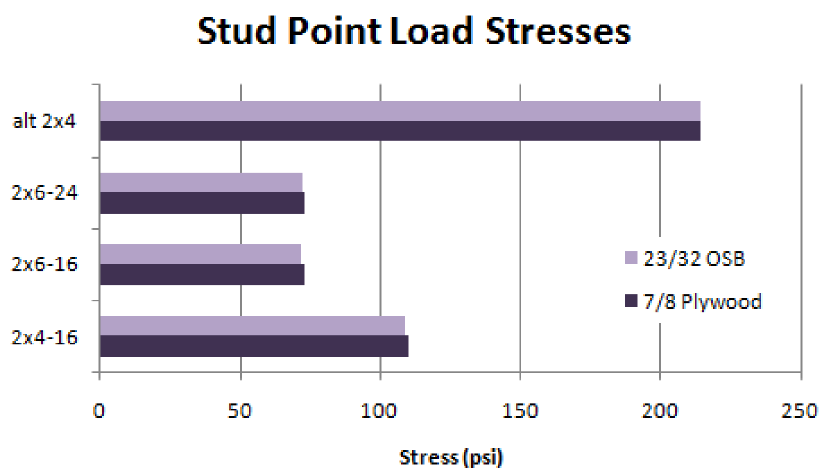

Figure 19: Stud point load stress

Figure 20 shows the maximum stress as a result of a point load on the sheathing or plaster board. The largest stress is in the gypsum board and the smallest stress is in the OSB board. The largest difference in stress among the models is 50 psi between the 16 in center distance and the 24 in center distance for the OSB sheathing.

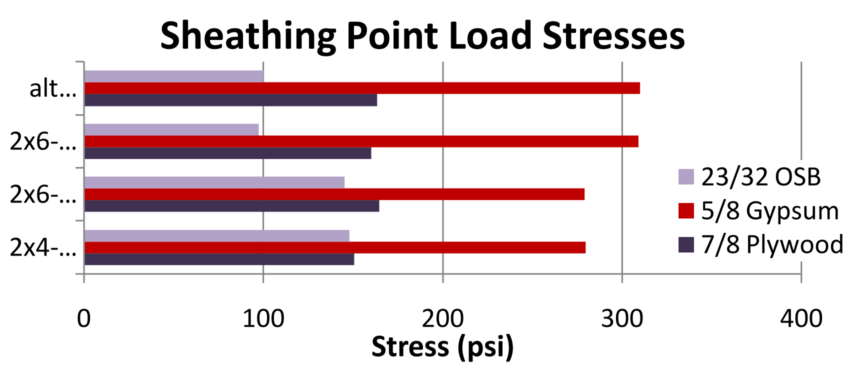

Figure 20: Sheathing point load stress

3.2 Heat Transfer

Figure 21 compares the heat loss from an 8 ft section of each model with ¾ in plywood sheathing with a temperature drop from 70F to 30F. The 2X4-16in center model had the highest heat loss. The 2X6-24in center model and the alternating stud model had the least amount of heat loss. The alternating model with air gaps had 19% and 30% more heat loss than the alternating stud model with full insulation at R-values of 3 and 4, respectively. The reduction in heat loss from an increase in R-value from 2 to 3 is greater than the reduction in heat loss as a result of an R-value increase from 3 to 4.

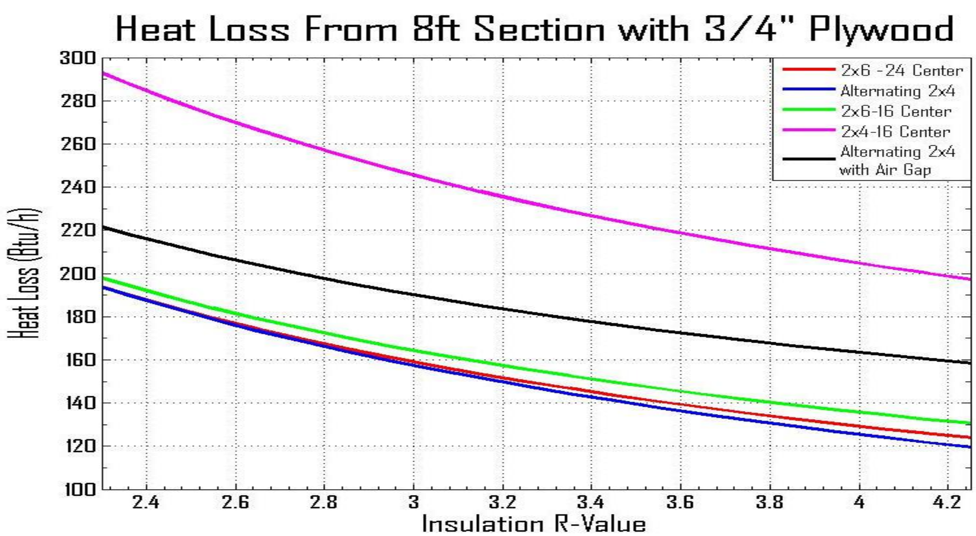

Figure 21: Heat loss for an 8ft section of each model

Figure 22 shows the heat loss in terms of various sheathing materials. Both of the OSB board thicknesses had less heat loss than the plywood. The thicker OSB sheathing of 23/24 in had 7% less heat loss at an insulation R-value of 3.6 than of 19/32 in.

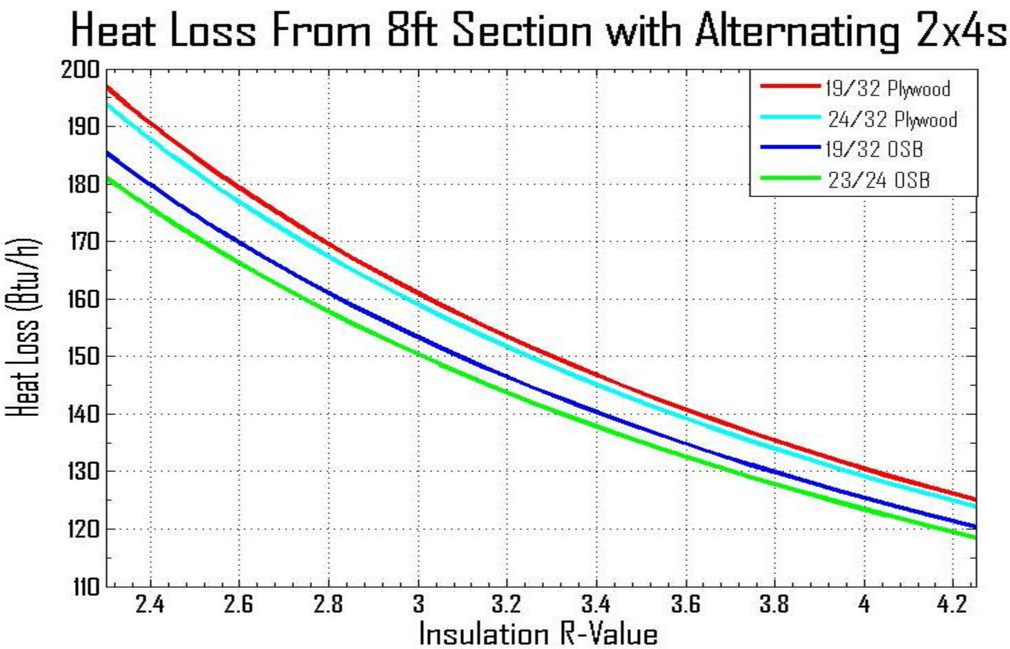

Figure 22: Heat loss from an 8 ft section with alternating 2X4s and various sheathing materials

Figure 23 shows the variation in heat loss as a result of the insulation gap between the stud and the wall. Both sheathing layers had the same change in heat loss. The effect of improper installation reduced for higher insulation R values.

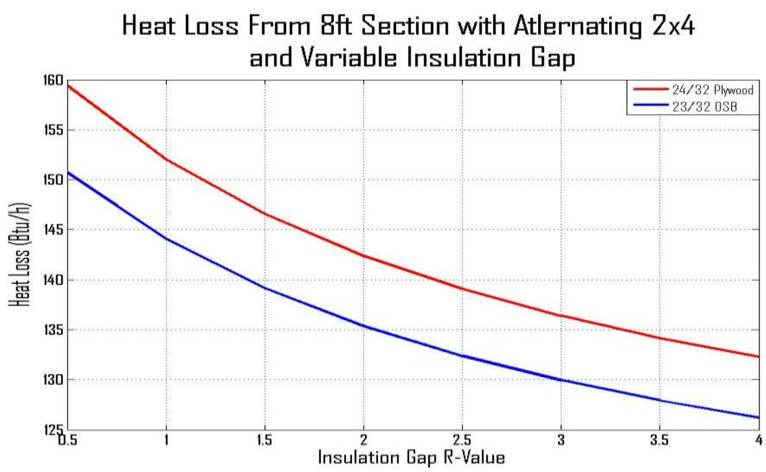

Figure 23: Heat loss as a result of various gap insulation

CHAPTER 4

DISCUSSION

This section discusses the implications and meaning behind the results obtained. Section 4.1 covers the structural results and compares them to the theoretical values. Section 4.2 assesses the heat transfer results and compares the loses. Section 4.3 discusses a cost benefit analysis of the various models with cost of construction compared to energy saved.

4.1 Structural

The structural analysis showed that the alternating 2X4 had the largest deflections. For horizontal loads on the studs the alternating 2X4 model had deflections that were 2.3 times greater than the 2X4 model. The applied deflections were on the exterior, and this showed how the gypsum board helps to strengthen the studs in terms of horizontal loads. Table 4 show the yield stress for the various building materials. The stresses are well below 9,700 psi yield stress for the stud. However, these deflections are much smaller than other deflections found due to point loads. The deflection as a result of point loads were comparable, with only a 7% difference, to those for the 2X6 24 in on center model. The deflections on the order of 0.1 in could be much more noticeable. While no investigation found experiments for the minimal amount of noticeable deflection, this similarity to 2X6-24 in on center model, which are acceptable construction method, indicate that this amount of deflection would be acceptable. Stresses were also much lower than the 600 psi rupture stress of the sheathing and gypsum layers. This shows that the alternative stud configuration is viable in terms of horizontal loads applied to the wall.

Table 4: Rupture stress for building materials

	gypsum	plywood	OSB	white western pine
Rupture Stress (psi)	660	6,530	7,250	9,700

The applied wind load showed largest deflections, of around 0.3 inches, with the alternating 2X4 model. The alternating 2X4 deflections were twice those of the 2X4 model and the stresses are 3.3 times greater. However, a stress of almost 5000 psi is lower than the 6,530 psi rupture stress of the sheathing layers. Thus, structurally, the wall would theoretically remain standing after the wind pressure load. These deflections were modeled for strong wind gusts, at which point visible deflections are not as important as a structural failure. In addition, the model does not account for the possible inclusion of siding which could also increase the rigidity of the wall and reduce deflections. Taking these factors into account, the alternating 2X4 behaves worse than the three other models, but is still acceptable structurally.

Comparing the two 2X6 models, there is no difference as a result of the stud loads, which would be expected. Point loads on the sheathing and gypsum did very, showing that the larger 24 in span does have greater deflection. The affect of the stud span on deflection depended on the material selected, either the more rigid plywood or OSB. In terms of wind load, the deflections for the 16 in model differed from the deflection of the 24 in model by 40%. Again, the extent of the deflections depended more on material. The 2X6 wall models were more rigid than the 2X4 wall for the 16 in on center model. The stud point loads, sheathing point loads, and wind load were respectively 1.5, 1.7, and 2.1 times greater for the 2X4 model than the 2X6 model. In all cases the stresses were less than the yield stress for the sheathing layers.

The choice in sheathing material has no effect worth noting in terms of the stresses and deflection as a result of point loads on the stud walls. Likewise, there is no meaningful difference in the stresses as a result of wind load. The deflection as a result of wind load did show dependence on the material selected. A 16 in span had 9% less deflection when using 7/8 plywood over 5/8 plywood. For the larger 24 in gaps this difference decreased to 20% less deflection. The 23/32 OSB had 15% less deflection with the 24 in span. In terms of point loads the gypsum board had the largest deflections, which were over 10 times greater for 24 in spans and over 5 times greater for the 16 in spans. The gypsum material would be what a house owner will typically interact with. It is thus the deflection of the gypsum board that will determine if the design is acceptable base on deflections.

All deflections were less than the 0.339 in deflections predicted by modeling the deflection on just the stud beam. The deflections of the stud were 62% and 1.3% of the predicted .339in for the alternating 2X4 and 2X6 models, respectively. This shows the roll that the sheathing layers had in reducing the deflection of the stud. The deflection due to wind load was .295 in for the OSB alternating 2X4 model, which was 67% of the 0.44in deflections predicted by the plate equations, Equation 3. The equations validate the results obtained for the given model constraints for the simulated deflections are on similar orders of magnitude.

Using a 2X6 16 in center model with 7/8 plywood was the most rigid design, which would be expected. The "flimsiest" design is the alternating stud model with 5/8 plywood. If 7/8 plywood is used instead of 5/8 plywood, the alternating model would not be significantly different from the common 2X6 24 inch on center model. This shows that in terms of the lateral load, the alternating model is an acceptable design.

4.2 Heat Transfer

The alternating 2X4 model with full insulation had the smallest heat loss of any model at an R-value of 3.7 with 135 BTUs/h per hour. However, if the region between the alternating 2X4 and the opposite wall was not filled with insulation, then the heat loss was increased 30% to 170 BTUs/h per hour which was still better than the 2X4 model. This shows that it is important to use blown in insulation instead of batt insulation, which would not be able to fill all the gaps in the alternating 2X4 wall. Figure 23 showed the need to have the wall cavity be completely filled with insulations. It is also important to notice that as the R-value increases, so does the need to fully fill all the gaps. The need to fully fill the wall cavity causes additional difficulty in blowing in the insulation over the simple current square cavities.

The standard 2X4 model had the largest heat loss of 215 BTUs/h per hour at an R-value of 3.7, which was larger than the alternating 2X4 with the gap unfilled. In relation to the 2X4 model, the percent difference in heat loss increased as the R-value increases. Increasing the R-value from 3 to 4 resulted in a percentage increase in heat loss from the alternating 2X4 of 53% and 64%, respectively. This demonstrates that as the R-value increases the impact of the wall selection decreases. This makes sense, because an R-value that is infinite would have no heat loss. However, walls with such high resistance to heat loss would be very expensive. So current wall selection does make a significant impact in the amount of heat lost.

In terms of the 2X6 models, the 16 in on center model had less heat loss than the 24 in on center span. However, the benefit of selecting the 24 in over the 16 in on center model improves the heat loss only 3% and 8% for an R-value of 3 and 4, respectively.

In comparing the 2X6 24 in on center model to the alternating 2X4, there is not a noticeable difference in heat loss until an R-value of approximately 3.6. At an R-value of 4 the reduction in heat loss by selecting the alternating 2X4 is 125Btu/h or only a 2% percent improvement from the 2X6 24 in on center model. The benefit of selecting the alternating 2X4 increases as the R-value increases, but the gains were marginal at best. However, if the most thermally efficient design is desired, then the alternating 2X4 would be the design selected.

In considering sheathing material, the thicker 23/24 inch thick OSB provided the least amount of heat loss. The thinner 18/32 plywood had heat losses of 163Btu/h, with an 8% decrease in loss for the 23/24 OSB and only 1% decrease with 24/32 Plywood, at an R-value of 3. This shows that the material selection is more important than the material thickness for the sheathing layer when considering thermal efficiency. Also, at higher insulation R-values, the impact of the sheathing layer on heat loss diminished. The percent difference in heat loss at an R-value of 4 between 18/32 plywood and 23/24 OSB was reduced by 4% from an R-value of 3. This showed that there is little reduction in heat transfer rates as a result of material selection for the sheathing layer; however the optimum material is 23/24 in thick OSB.

From the ANSYS model, a loss 5.12 BTUs/h/h of energy was predicted for the half a foot by 3.98 ft quarter section of the wall. For a full 8 ft section this predicted a loss of 163.8 BTUs/h of energy loss. From Figure 22, the heat loss was calculated to be approximately 160 BTUs/h for plywood sheathing layers. Thus, the error between the models is less than 1%. This shows agreement between the ANSYS heat transfer solution and the simple analytical solution. Thus, to predict total heat transfer, the use of the analytical equations gave acceptable results.

Overall the most thermally efficient design is the alternating 2X4 with 23/24 OSB sheathing, which is marginally better than the 2X6 24 in on center model. The least efficient model, in terms of heat loss, is the standard 2X4 model with plywood as the sheathing layer.

4.3 Cost

Both the thermal analysis and the structural analysis showed that all models are structurally viable with various levels of heat loss with each model. However, the financial goal of reducing heat is to save money long term by building a more efficient house and thus reducing heating costs. This also ties into the concept of selecting a more sustainable design, which comes into play when a design uses more resources to reduce heat loss. Section 4.3.1 discusses the cost of the materials for each design. Section 4.3.2 discusses the financial impact of each wall model.

4.3.1 Material Cost and Calculation

The cost for each wall ignored the additional cost of labor and transportation. It assumes that each piece was purchased individually, which is not typical. The costs were found online from the home improvement store, House Depot. Table 5 proves a breakdown of the number of materials used and the cost per each material, and then the total cost for an 8ft section of wall.

Table 5: Cost of materials

		Number of Items per 8ft Section			
Material	cost ($)	Alternating Studs	2x6 - 16 Center	2x6-24 Center	2x4-16 Center
2x4 Lumber Model 161640	$2.57	8	----	----	6
2x6 Lumber Model 2493	$3.67	2	6	4	----
23/32 OSB Model 637367	$13.47	2	2	2	2
3/4 Millstead Plywood 4Ft. x 8 Ft.	$22.42	2	2	2	2
20 lb bag of Cellulous Insulation	$9.89	1.286	1.283	1.328	0.816
	Total Cost OSB	$67.56	$61.65	$54.75	$50.43
	Total Cost Plywood	$85.46	$79.55	$72.65	$68.33

4.3.2 Cost Comparisons

To compare the costs associated with material selection in house construction, the size of the house first needs to be assessed. This is because the surface area directly correlates to heat loss. Figure 24 shows the heat loss as a function of an idealized house in terms of square footage. The idealized house is one that is just a box with an insulated top and bottom and with four walls that, regardless of the actual dimensions, are constructed as repeating 8 ft sections. While this would never occur in a house, it provides a means of comparing the impact of the house size. From Figure 24, it can be seen that the all models that use a 2X6 base frame have similar heat loss, with the alternating 2X4 being the lowest. The standard 2X4 model heat loss is 70% greater at 1000 square feet than the other models, and the difference in heat loss increase as the square footage increase.

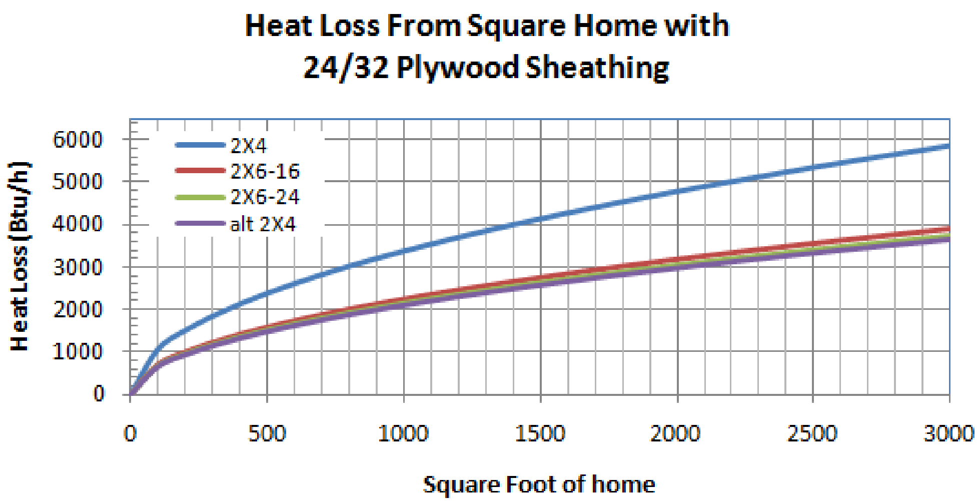

Figure 24: Heat loss in terms of houses size

The house size for comparison was assumed to be around 2000 square feet. Thus, Figure 25 shows the heating cost for a cold month as a function of the cost per kwatthour for the energy lost from a 2000 square foot idealized house. This shows that for the current cost of 10 cents per kwatthour[3], the difference in energy savings by constructing either a 2X6 model or the

[3] Kwatthour was used for cost analysis to provide a direct relation to typical bill charges in the Ohio. To convert BTUs to Kwatthours a conversion of 3142 BTU equals 1 kwatthour was used.

alternating 2X4 over a standard 2X4 is about 30 dollars per cold month. It also shows that as energy increases above 30cents per kwatthour, there is a benefit of 5 dollars per month in selecting the 2X6 24 in on center model over the 16in on center model. However, at 30 cents the benefit of selecting the alternating 2X4 over the 2X6 24 in on center model is about 2 dollars.

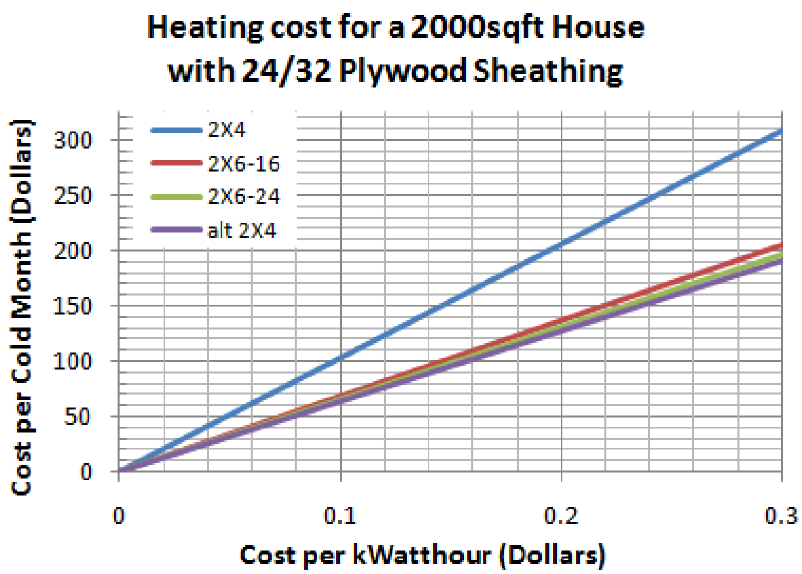

Figure 25: Cost for heating as a function of cost per kWh

One of the benefits of a more efficient house is that the reduced cost saves money for the house owner. However, if it costs more to build a wall than the money saved over the lifetime of the house, then there is no benefit for the house owner in choosing a more efficient design. Using the costs found in Figure 25 and the material cost from Table 5, Figure 26 was derived. Figure 26 shows the number of cold months until the material costs is paid for in the energy savings over building the cheapest house using the base 2X4 model with OSB. This analysis ignored construction hours or any other additional costs, for they were treated as fixed for all considerations. This assumption would reduce the percent difference between building methods;

however, the payback would be the same because the additional costs would be for a 2X4 model as well. Also, when considering cold months, it is important to note that these deal with average exterior temperatures of 30°F. This temperature average is typically reached during the end of December to the beginning of March, which means that there are at most three cold months a year.

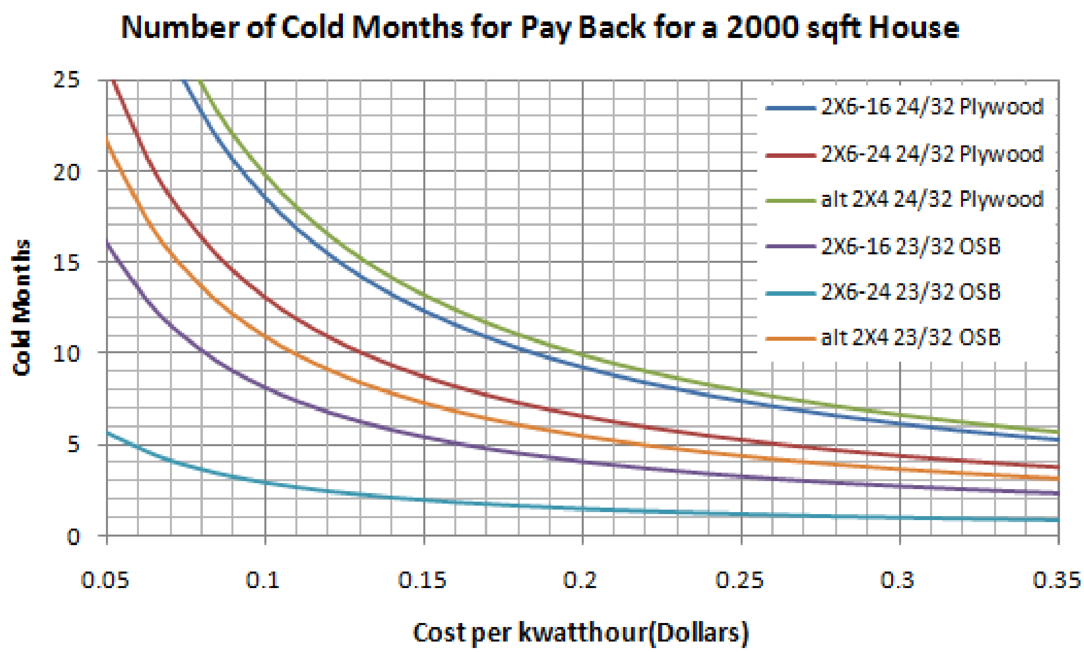

Figure 26: Cold Months for Pay Back

From Figure 26, the design with the shortest payback period is the 2X6 24 in on center model with OSB sheathing with three cold months, or just one year. This means that in choosing to build a 2x6 24 in on center wall with OSB over a standard 2X4 model that within approximately 3 months the energy saved at a cost of 10 cents per kwatthour will pay for the additional material costs. The model with the next shortest payback period is the 2X6 16 in on center model and then the alternating 2X4 with OSB sheathing. Plywood increases the payback period, or, if plywood would have been used for the 2X4 base model, using OSB reduces the payback period. Either way, the selection of OSB has a noticeable effect on the final payback period. It is also important to note that as the cost of energy increases the payback period for all models reduces. Table 6 is a list of the payback periods for the various conditions at a cost of 10 cents and 25 cents per kwatthour with red indicating a loss and green indicating a financial gain.

Table 6: Rate of return for various materal selcetion

Rate of Return for 5 years with Inflation of 3% (compared to 2x4 OSB wall)		
Cost per kwatthour ($)	$0.10	$0.25
2x6-16 Plywood	-18.29%	-1.86%
2x6-16 OSB	1.22%	21.58%
2x6-24 Plywood	-11.91%	5.81%
2x6-24 OSB	24.62%	49.68%
Alt 2x4 Plywood	-18.76%	-2.43%
Alt 2x4 OSB	-4.59%	14.60%

Table 6 shows that the 5 year rate of return for building one of the more efficient models over the standard 2X4 with an inflation of 3%. Only the two 2X6 with OSB designs offer a positive rate of return over constructing a standard 2X4 model at a cost of 10 cents per kwatthour. At a cost of 25 cents per kwatthour only the 2X6 16 in span and alternating 2X4 models with plywood have a negative rate of return. Also, at a cost of 25 cents, the rate of return for the 2X6 24 in with OSB is almost 50%. This shows that, while the alternating 2X4 is the most efficient model in term of heat transfer, the 2X6 24 in span is the most efficient model in term of total cost for the design.

CHAPTER 5

FUTURE WORK AND SUMMARY

This chapter discusses the limitations of the thesis, possible improvement, suggested direction for future work, and provides a summary of the results. Section 5.1 discusses the limitations of the study and future considerations. Section 5.2 summarizes the thesis.

5.1 Future Work

The models done for these simulations just focused on a house wall. However, there are many other factors that determine the thermal efficiency of a house. Most notably the idealized house did not include windows, doors, or a basement. All three can have less thermal resistance than the modeled walls, which would reduce the impact of selecting the more efficient model. There are other decisions in terms of house design that can affect to what extent the overall house efficiency benefits from a more efficient wall design. The next step would be to quantify how the door, window, basement, wall, roof design, and construction methods impact the thermal efficiency of a single story square house. The key in this investigation would be to look into the number and size of the windows and doors. Doing this will show what model is the most efficient single story house in terms of component design and what components are most significant in house design.

An assumption that was made to make modeling easier to perform was to treat the sheathing and gypsum layers as being rigidly connection to the edge of the 2X4 or 2X6 studs. This caused the structure to be more rigid than it would be in construction. The type of fastener and the spacing between each attachment point affect how rigid the sheathing and gypsum behave. Also, in using nails or staples, stress concentrations are introduced which can weaken the layers, particularly the gypsum board. The connection of the studs to the base and top framing was treated as rigid. The method used to attach the studs to the frame, in particular the connector plate selected, affects how accurately a rigid assumption models the house wall. The effects of attaching the boards to the studs need to be assessed to validate the structural results obtained in this thesis.

Only horizontally applied loads were applied to the models. The possible loads from the roof of the house, and it possible contents, was not considered in the model. These loads can induce vertical and additional horizontal loads due to bending moments on the wall which adds stress to the studs. While there is little concern that the distributed weight of the roof would invalidate the results, the inclusion of additional weight due to snow and other weather related weights might cause loading that would be of concern for the alternating 2X4 model. The impact of these additional loads would need to be assessed for the alternating 2X4 method.

The method for testing inclusion of gaps assumed a reduction in the house wall R-value. However, at no point was the geometry of a gap implemented or an assessment run to find what the actual impact on the R-value a gap of various sizes would have. While any reduction in R-value is not desired, the impact of the gap on the R-value would be helpful in determining the impact of poor installation. It is thus recommended that the affect of insulation gaps of various sizes on the heat transfer rates be assessed.

Finally, no siding was used in any of the models. The selection of siding is highly variable with many different materials and geometries. The inclusion of siding could make the walls more rigid to wind loads, and possibly, depending on location, exterior point loads. While there was no concern in the results for applied exterior loads, siding could further strengthen a wall. Also, again depending on the siding selection, there could be a small increase in thermal efficiency as well. Although with the added cost, it might not be economically beneficial. Thus, future investigations might want to consider assessing the increase in rigidity and thermal efficiency, in terms of pay pack.

5.2 Summary

The goal of the thesis was to determine the impact of the stud configuration of the exterior wall in terms of structural strength, heat loss, and cost. The results showed that an alternating 2X4 is a structurally viable design and is the most efficient stud configuration with heat loss of 135 BTUs/h per hour. However, the alternating 2X4 model had only 2% less heat loss than the 2X6 24 in on center model. Both 2X6 models and the alternating stud model were similar in term of heat loss, and did not deviate more than 10% from each other. The standard 2X4 stud model had 62.7% more heat loss than the alternating 2X4, or 215 BTUs/h per hour. Finally the need to fill in the gap was also shown with a heat loss of 170 BTUs/h per hour if not filled in. What the heat transfer results show is that the thickness of the wall is the most important aspect of the wall, in terms of heat transfer.

Structurally the alternating 2X4 was the model with the greatest deflection and stress for all applied loads. The deflections were twice those of the 2X4 stud model. However, the stress was never greater than the rupture stress of any material for any model. The deflections were under .025in for the exterior sheathing layers. The gypsum board had the largest deflections with both the alternating 2X4 and 2X6 24in on center model being between .1in and .12in. The gypsum board also had the largest stress due to point loads of around 300psi. While this is less than the rupture stress, possible cracking and failure at the nail joint needs to be assessed.

In terms of cost however, the alternating 2X4 wall was significantly less effective than a 2X6 model of the same sheathing material. Based on cost from local timber stores and excluding any variation in labor costs, the 2X6 16 in center and 2X6 24 in center models had the only positive five year rate of return using those models instead of the 2X4 model with OSB at a power cost of 10 cents per kwatthour. If the cost of a kwatthour rises to 25 cents then alternating 2X4 model had a five year rate of return of 14.6%. However, the 2X6 24 in center model had 49.68% five year rate of return over the 2X4 model with OSB.

Overall, the calculations show that while viable, the 2X6 24in on center model is preferred over the alternating 2X4. In terms of heat transfer the two models are similar. However, in terms of structural strength and cost the 2X6 24in on center model is the superior model. The difficulty in fully insulating the alternating model, the fact that it is marginally more difficult to construct the alternating pattern, and that it has a higher material cost outweighs the fact that it is the most efficient model in terms of heat transfer. It is the recommendation of this thesis to use a 2X6 24in on center model in exterior wall construction

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APPENDIX

Appendix A: Heat Loss Code

```
%Code to show heat loss due to wall configuration layers value
%Matthew Hansen

clear
clc
%2x6 wood
wood=.066/144;              %Wood conductivity inch
wl=5.5;                     %wood thickness
wA=(1.5*92.625+3*24)/4;     %wood area
Rwood=wl/(wood*wA);         %Thermal resistance of wood

osb=.032/144;               %osb conductivity inch
ol=23/32;                   %osb length
oA=95.63*24/4;              %osb area
Rosb=ol/(osb*oA);           %osb thermal resistance

ply=.066/144;               %plywood conductivity inch
pl=24/32;                   %plywood thickness
pA=95.63*24/4;              %plywood area
Rply=pl/(ply*pA);           %thermal resistance of plywood

gyp=.093/144;               %gypsum conductivity inch
gl=4/8;                     %gypsum thickness
gA=pA;                      %gypsum area
Rgyp=gl/(gyp*gA);           %theramal resistance of gypsum

Rvalue=3.7;                 %Insulation Rvalue
insul=(Rvalue*12).^-1       %converting to thermal resistance
insul=insul./144;           %putting in terms of inches
il=5.5;                     %insulation thickness
iA=pA-wA;                   %insulation area
Rinsul=il./(insul.*iA);     %thermal resistance of insulation

tc=30;                      %temperature cold
th=70;                      %temperature hot
dt=th-tc;                   %temperature gradient
```

```
qallo26= dt./(Rosb+Rgyp+(1./(Rwood)+1./Rinsul).^-1); %heat flux for osb
loss26osb=qallo26*12*2*2 %heat loss for osb

%plywood
qallp26= dt./(Rply+Rgyp+(1./(Rwood)+1./Rinsul).^-1); %heat flus for plywood
loss26ply=qallp26*12*2*2 %heat loss for plywood

%derivations the same for all wall configurations
%alt 2x4
wl=5.5;
wA=1.5*12;
Rwoodtb=wl/(wood*wA);
wsl=3.5;
wsA=1.5*(92.625)/2;
Rwoodstud=wsl/(wood*wsA);

oA=95.63*12/2;
Rosb=ol/(osb*oA);

gA=oA;
Rgyp=gl/(gyp*gA);

il=5.5;
iA=(12-1.5)*92.625/2;
Rinsul=il./(insul.*iA);

insulgap=insul;
igl=2;
igA=1.5*92.625/2;
Rgap=igl./(insulgap.*igA);

qalloalt= dt./(Rosb+Rgyp+(1./(1./(Rwoodstud+Rgap)+1/Rwoodtb).^-
1+1./Rinsul).^-1);

lossaltosb=qalloalt*12*2*2

%plywood
qallpalt= dt./(Rply+Rgyp+(1./(1./(Rwoodstud+Rgap)+1/Rwoodtb).^-
1+1./Rinsul).^-1);
lossaltply=qallpalt*12*2*2

%2x6-16
wl=5.5;
wA=(1.5*92.625+3*16)/4;
Rwood=wl/(wood*wA);

oA=95.63*16/4;
Rosb=ol/(osb*oA);

gA=oA;
Rgyp=gl/(gyp*gA);
```

```
iA=oA-wA;
Rinsul=il./(insul*iA);

qallo2616= dt./(Rosb+Rgyp+(1./(Rwood)+1./Rinsul).^-1);
loss2616osb=qallo2616*12*2*3

%plywood
qallp2616= dt./(Rply+Rgyp+(1./(Rwood)+1./Rinsul).^-1);
loss2616ply=qallp2616*12*2*3

%2x4
wl=3.5;
wA=(1.5*92.625+3*16)/4;
Rwood=wl/(wood*wA);

oA=95.63*16/4;
Rosb=ol/(osb*oA);

gA=oA;
Rgyp=gl/(gyp*gA);

il=3.5;
iA=oA-wA;
Rinsul=il./(insul*iA);

qallo24= dt./(Rosb+Rgyp+(1./(Rwood)+1./Rinsul).^-1);
loss24osb=qallo24*12*2*3

%plywood
qallp24= dt./(Rply+Rgyp+(1./(Rwood)+1./Rinsul).^-1);
loss24ply=qallp24*12*2*3

%plots
plot(Rvalue,loss26ply,'red')
hold on
plot(Rvalue, lossaltply, 'blue')
plot(Rvalue, loss2616ply, 'green')
plot(Rvalue, loss24ply, 'magenta')
plot(Rvalue,loss26osb,'red')
plot(Rvalue, lossaltosb, 'blue')
plot(Rvalue, loss2616osb, 'green')
plot(Rvalue, loss24osb, 'magenta')
grid on
```

```
%Code to show heat loss due to various sheathing layers value
%Matthew Hansen

clear
clc
%2x6 wood
wood=.066/144;              %Wood conductivity inch
wl=5.5;                     %wood thickness
wA=(1.5*92.625+3*24)/4;     %wood area
Rwood=wl/(wood*wA);         %Thermal resistance of wood

pA=95.63*24/4;              %plywood area

Rvalue=3.7;                 %Insulation Rvalue
insul=(Rvalue*12).^-1       %converting to thermal resistance
insul=insul./144;           %putting in terms of inches
il=5.5;                     %insulation thickness
iA=pA-wA;                   %insulation area
Rinsul=il./(insul.*iA);     %thermal resistance of insulation

tc=30;                      %temperature cold
th=70;                      %temperature hot
dt=th-tc;                   %temperature gradient

gyp=.093/144;               %gypsum conductivity inch
gl=4/8;                     %gypsum thickness
gA=pA;                      %gypsum area
Rgyp=gl/(gyp*gA);           %theramal resistance of gypsum

%OSB-19/32
osb=.032/144;               %osb conductivity inch
ol=23/32;                   %osb length
oA=95.63*24/4;              %osb area
Rosb=ol/(osb*oA);           %osb thermal resistance

qallp26= dt./(Rply+Rgyp+(1./(Rwood)+1./Rinsul).^-1) %heat flux
loss26=qallp26*12*2*2*4   %heat loss

%derivations the same for all wall configurations


%OSB-23/32
osb=.032/144;
ol=23/32;
oA=95.63*24/4;
Rosb=ol/(osb*oA);

qallp26= dt./(Rosb+Rgyp+(1./(Rwood)+1./Rinsul).^-1);
loss26osb23=qallp26*12*2*2*4

%plywood-19/32
```

```
ply=.066/144;
pl=19/32;
pA=95.63*24/4;
Rply=pl/(ply*pA);

qallp26= dt./(Rply+Rgyp+(1./(Rwood)+1./Rinsul).^-1);
loss26ply19=qallp26*12*2*2*4

%plywood-24/32
ply=.066/144;
pl=24/32;
pA=95.63*24/4;
Rply=pl/(ply*pA);

qallp26= dt./(Rply+Rgyp+(1./(Rwood)+1./Rinsul).^-1);
loss26ply24=qallp26*12*2*2*4

%plots
plot(Rvalue,loss26ply19,'red')
hold on
plot(Rvalue,loss26ply24,'cyan')
plot(Rvalue,loss26osb19,'blue')
plot(Rvalue,loss26osb23,'green')
grid on
ylabel('Heat Loss (BTUs/h/h)')
xlabel('Insulation R-Value')
title('Heat Loss from 8ft section')



%Code to show variation in heat loss due to gap R value
%Matthew Hansen
clear
clc

%2x6 wood
wood=.066/144;              %Wood conductivity inch
wl=5.5;                     %wood thickness
wA=(1.5*92.625+3*24)/4;     %wood area
Rwood=wl/(wood*wA);         %Thermal resistance of wood

osb=.032/144;               %osb conductivity inch
ol=23/32;                   %osb length
oA=95.63*24/4;              %osb area
Rosb=ol/(osb*oA);           %osb thermal resistance

ply=.066/144;               %plywood conductivity inch
pl=24/32;                   %plywood thickness
pA=95.63*24/4;              %plywood area
Rply=pl/(ply*pA);           %thermal resistance of plywood
```

```
gyp=.093/144;               %gypsum conductivity inch
gl=4/8;                     %gypsum thickness
gA=pA;                      %gypsum area
Rgyp=gl/(gyp*gA);           %theramal resistance of gypsum

Rvalue=3.7;                 %Insulation Rvalue
insul=(Rvalue*12).^-1       %converting to thermal resistance
insul=insul./144;           %putting in terms of inches
il=5.5;                     %insulation thickness
iA=pA-wA;                   %insulation area
Rinsul=il./(insul.*iA);     %thermal resistance of insulation

tc=30;                      %temperature cold
th=70;                      %temperature hot
dt=th-tc;                   %temperature gradient

qallp26= dt./(Rply+Rgyp+(1./(Rwood)+1./Rinsul).^-1) %heat flux
loss26=qallp26*12*2*2*4  %heat loss

%derivations the same for all wall configurations

%alt 2x4
wl=5.5;
wA=1.5*12;
Rwoodtb=wl/(wood*wA);
wsl=3.5;
wsA=1.5*(92.625)/2;
Rwoodstud=wsl/(wood*wsA);

pA=95.63*12/2;
Rply=pl/(ply*pA);

gA=pA;
Rgyp=gl/(gyp*gA);

il=5.5;
iA=(12-1.5)*92.625/2;
Rinsul=il./(insul.*iA);

insulgap=insul;
igl=2;
igA=1.5*92.625/2;
Rgap=igl./(insulgap.*igA);

qallpalt= dt./(Rply+Rgyp+(1./(1./(Rwoodstud+Rgap)+1/Rwoodtb).^-
1+1./Rinsul).^-1)
lossaltply=qallpalt*12*2*2*4

%alt with air in gap

Rvgap=.5:.5:4
```

```
insulgap=(Rvgap*12).^-1./144;
igl=2;
igA=1.5*92.625/2;
Rgap=igl./(insulgap.*igA);

qallpalt= dt./(Rply+Rgyp+(1./(1./(Rwoodstud+Rgap)+1./Rwoodtb).^-
1+1./Rinsul).^-1);
lossaltairply=qallpalt*12*2*2*4

%osb alt
qalloalt= dt./(Rosb+Rgyp+(1./(1./(Rwoodstud+Rgap)+1/Rwoodtb).^-
1+1./Rinsul).^-1);
lossaltairosb=qalloalt*12*2*2*4

%plots
plot(Rvgap, lossaltairply, 'red')
hold on
plot(Rvgap, lossaltairosb)
grid on
grid on
ylabel('Heat Loss (BTUs/h/h)')
xlabel('Insulation Gap R-Value')
title('Heat Loss from 8ft section')
```